

## Flavor and Spin Structure of $\Lambda$ -Baryon at Large $x$

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### Abstract

It is shown that a perturbative QCD (pQCD) based analysis and the SU(6) quark-diquark model give significant different predictions concerning the flavor and spin structure for the quark distributions of the  $\Lambda$ -baryon near  $x = 1$ . Detailed predictions for the ratios  $u(x)/s(x)$  of unpolarized quark distributions,  $\Delta s(x)/s(x)$  of valence strange quark, and  $\Delta u(x)/u(x)$  of valence up and down quarks of the  $\Lambda$  are given from the quark-diquark model and from a pQCD based model. It is found that the up and down quarks are positively polarized at large  $x$ , even though their net spin contributions to the  $\Lambda$  might be zero or negative. The significant difference for  $u(x)/s(x)$  between the two different approaches are predicted. The prediction of positively polarized up and down quarks inside the  $\Lambda$  at large  $x$  has been supported by the available data of  $\Lambda$ -polarization in  $Z$  decays and also by the most recent HERMES result of spin transfer to the  $\Lambda$  in deep elastic scattering of polarized lepton on the nucleon target.

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Although it is well established knowledge that hadrons are composite systems of quarks and gluons, the detailed quark structure of hadrons remains a domain with many unknowns, and there have been many unexpected surprises with respect to naive theoretical considerations. The sea content of the nucleons has received extensive investigations concerning its spin structure [1], strange content [2, 3], flavor asymmetry [4], and isospin symmetry breaking [5], and it is commonly taken for granted that our understanding of the valence quark structure of the nucleons is more clear. However, even in this last case the situation remains doubtful, reflected in the recent investigations concerning the flavor and spin structure of the valence quarks for the nucleon near  $x = 1$ . For example, there are different predictions concerning the ratio  $d(x)/u(x)$  at  $x \rightarrow 1$  from a perturbative QCD (pQCD) based analysis [6, 7] and the SU(6) quark-diquark model [8, 9, 10], and there are different predictions concerning the value of  $F_2^n(x)/F_2^p(x)$  at large  $x$ , which has been taken to be  $1/4$  as in the quark-diquark model in most parameterizations of quark distributions. A recent analysis [11] of experimental data from several processes suggests that  $F_2^n(x)/F_2^p(x) \rightarrow 3/7$  as  $x \rightarrow 1$ , in favor of the pQCD based prediction. The spin structure of the valence quarks is also found to be different near  $x = 1$  in these models, and predictions have been made concerning the non-dominant valence down ( $d$ ) quark, so that  $\Delta d(x)/d(x) = -1/3$  in the quark-diquark model [9, 10], a result which is different from the pQCD based prediction  $\Delta q(x)/q(x) = 1$  for either  $u$  and  $d$  [7]. At the moment, there is still no clear data in order to check these different predictions, although the available measurements [13] for the polarized  $d$  quark distributions seem to be negative at large  $x$ , slightly in favor of the quark-diquark model prediction.

In this letter, we show that the same mechanisms that produce the different flavor and spin structure for the quark distributions of the nucleon, give also significant different predictions concerning the flavor and spin structure for the quark distributions of the  $\Lambda$ -baryon near  $x = 1$ , thus providing tests of different approaches. We also show that the non-dominant up ( $u$ ) and down ( $d$ ) quarks of the  $\Lambda$  should be positively polarized at large  $x$ , even though their net spin contributions to the  $\Lambda$  might be zero or negative. In fact, it was found by Burkardt and Jaffe [14] that the

$u$  and  $d$  quarks should be negatively polarized from SU(3) symmetry. Recently, it was also pointed out by Soffer and one of us [15] that the flavor and spin content of the  $\Lambda$  can be used to test different predictions concerning the spin structure of the nucleon and the quark-antiquark asymmetry of the nucleon sea. Thus it is clear that the quark structure of  $\Lambda$  is a frontier with rich physics and deserves further attention both theoretically and experimentally.

We now look into the details of the flavor and spin structure for the valence quarks of the  $\Lambda$ . We start our analysis in the SU(6) quark-diquark model. We know that exact SU(6) symmetry in the SU(6) quark model predicts  $u(x) = 2d(x)$  for the proton and this gives the prediction  $F_2^n(x)/F_2^p(x) \geq 2/3$  for all  $x$ . This result was ruled out by the experimental observation that  $F_2^n(x)/F_2^p(x) < 1/2$  for  $x \rightarrow 1$ , where the valence quark contributions are dominant. The SU(6) quark-diquark model [8] introduces a breaking to the exact SU(6) symmetry by the mass difference between the scalar and vector diquarks and predicts  $d(x)/u(x) \rightarrow 0$  at  $x \rightarrow 1$ , leading to a ratio  $F_2^n(x)/F_2^p(x) \rightarrow 1/4$  which could fit the data and has been accepted in most parameterizations of quark distributions for the nucleon. In this work we analyze the valence quark distributions of the  $\Lambda$  by extending the SU(6) quark-spectator-diquark model [9], which can be considered as a revised version of the original SU(6) quark-diquark models [8], from the nucleon case to the  $\Lambda$ . The  $\Lambda$  wave function in the conventional SU(6) quark model is written as

$$|\Lambda^\uparrow\rangle = \frac{1}{2\sqrt{3}}[(u^\uparrow d^\downarrow + d^\downarrow u^\uparrow) - (u^\downarrow d^\uparrow + d^\uparrow u^\downarrow)]s^\uparrow + (\text{cyclic permutation}), \quad (1)$$

which can be reorganized into the SU(6) quark-diquark model wave function,

$$\begin{aligned} |\Lambda^\uparrow\rangle &= \frac{1}{\sqrt{12}}[V_0(ds)u^\uparrow - V_0(us)d^\uparrow - \sqrt{2}V_{+1}(ds)u^\downarrow + \sqrt{2}V_{+1}(us)d^\downarrow \\ &+ S(ds)u^\uparrow + S(us)d^\uparrow - 2S(ud)s^\uparrow], \end{aligned} \quad (2)$$

where  $V_{s_z}(q_1 q_2)$  stands for a  $q_1 q_2$  vector diquark Fock state with third spin component  $s_z$ , and  $S(q_1 q_2)$  stands for a  $q_1 q_2$  scalar diquark Fock state.

From Eq. (2) we get the unpolarized quark distributions for the three valence  $u$ ,

$d$ , and  $s$  quarks for the  $\Lambda$ ,

$$\begin{aligned} u_v(x) &= d_v(x) = \frac{1}{4}a_{V(qs)}(x) + \frac{1}{12}a_{S(qs)}(x); \\ s_v(x) &= \frac{1}{3}a_{S(ud)}(x), \end{aligned} \quad (3)$$

where  $a_{D(q_1q_2)}(x) \propto \int [d^2\vec{k}_\perp] |\varphi(x, \vec{k}_\perp)|^2$  ( $D = S$  or  $V$ ) denotes the amplitude for the quark  $q$  being scattered while the spectator is in the diquark state  $D$ , and is normalized such that  $\int_0^1 a_{D(q_1q_2)}(x) dx = 3$ . We assume the  $u$  and  $d$  symmetry  $D(qs) = D(us) = D(ds)$ , from the  $u$  and  $d$  symmetry inside  $\Lambda$ . Similarly, the quark spin distributions for the three valence quarks can be expressed as,

$$\begin{aligned} \Delta u_v(x) &= \Delta d_v(x) = -\frac{1}{12}a_{V(qs)}(x) + \frac{1}{12}a_{S(qs)}(x); \\ \Delta s_v(x) &= \frac{1}{3}a_{S(ud)}(x). \end{aligned} \quad (4)$$

In order to perform the calculation, we employ the Brodsky-Huang-Lepage prescription [16] for the light-cone momentum space wave function for the quark-spectator  $\varphi(x, \vec{k}_\perp) = A_D \exp\{-\frac{1}{8\alpha_D^2}[\frac{m_q^2 + \vec{k}_\perp^2}{x} + \frac{m_D^2 + \vec{k}_\perp^2}{1-x}]\}$ , with parameters (in units of MeV)  $m_q = 330$  for  $q = u$  and  $d$ ,  $m_s = 480$ ,  $\alpha_D = 330$ ,  $m_{S(ud)} = 600$ ,  $m_{S(qs)} = 750$ , and  $m_{V(qs)} = 950$ , following Ref.[9]. The differences in the diquark masses  $m_{S(ud)}$ ,  $m_{S(qs)}$ , and  $m_{V(qs)}$  cause the symmetry breaking between  $a_{D(q_1q_2)}(x)$  in a way that  $a_{S(ud)}(x) > a_{S(qs)}(x) > a_{V(qs)}(x)$  at large  $x$ .

Thus the quark-diquark model predicts, in the limit  $x \rightarrow 1$ , that  $u(x)/s(x) \rightarrow 0$  for the unpolarized quark distributions,  $\Delta s(x)/s(x) \rightarrow 1$  for the dominant valence  $s$  quark which provides the quantum numbers of strangeness and spin of the  $\Lambda$ , and also  $\Delta u(x)/u(x) \rightarrow 1$  for the non-dominant valence  $u$  and  $d$  quarks.

We now look at the pQCD based analysis of the quark distributions from minimally connected tree graphs of hard gluon exchanges [6, 7]. In the region  $x \rightarrow 1$  such approach can give rigorous predictions for the behavior of distribution functions [7]. In particular, it predicts ‘‘helicity retention’’, which means that the helicity of a valence quark will match that of the parent nucleon. Explicitly, the quark distributions of a hadron  $h$  have been shown to satisfy the counting rule [18],

$$q_h(x) \sim (1-x)^p, \quad (5)$$

where

$$p = 2n - 1 + 2\Delta S_z. \quad (6)$$

Here  $n$  is the minimal number of the spectator quarks, and  $\Delta S_z = |S_z^q - S_z^h| = 0$  or  $1$  for parallel or anti-parallel quark and hadron helicities, respectively [7]. Therefore the anti-parallel helicity quark distributions are suppressed by a relative factor  $(1 - x)^2$ , and  $\delta q(x)/q(x) \rightarrow 1$  as  $x \rightarrow 1$ . A further input into the model, explained in detail in Ref. [7], is to retain the SU(6) ratios only for the parallel helicity distributions at large  $x$ , since in this region SU(6) is broken into  $SU(3)^\uparrow \times SU(3)^\downarrow$ . With such power-law behaviors of quark distributions, the ratio  $d(x)/u(x)$  of the nucleon was predicted [6] to be  $1/5$  as  $x \rightarrow 1$ , and this gives  $F_2^n(x)/F_2^p(x) = 3/7$ , which is (comparatively) close to the quark-diquark model prediction  $1/4$ . From the different power-law behaviors for parallel and anti-parallel quarks, one easily finds that  $\Delta q/q = 1$  as  $x \rightarrow 1$  for any quark with flavor  $q$  unless the  $q$  quark is completely negatively polarized [7]. Such prediction are quite different from the quark-diquark model prediction that  $\Delta d(x)/d(x) = -1/3$  as  $x \rightarrow 1$  for the nucleon [9, 10]. The most recent analysis [11] of experimental data for several processes supports the pQCD based prediction of the unpolarized quark behaviors  $d(x)/u(x) = 1/5$  as  $x \rightarrow 1$ , but there is still no definite test of the polarized quark behaviors  $\Delta d(x)/d(x)$  since the  $d$  quark is the non-dominant quark for the proton and does not play a dominant role at large  $x$ . Furthermore, this pQCD based model has been successfully used in order to explain the large single-spin asymmetries found in many semi-inclusive hadron-hadron reactions, while other models have not been able to fit the data [12].

We extend the pQCD based analysis from the proton case to the  $\Lambda$ . From the SU(6) wave function of the  $\Lambda$  we get the explicit total spin distributions for each valence quark,

$$\begin{aligned} u^\uparrow &= d^\uparrow = \frac{1}{2}; & u^\downarrow &= d^\downarrow = \frac{1}{2}; \\ s^\uparrow &= 1; & s^\downarrow &= 0, \end{aligned} \quad (7)$$

for all values of  $x$ . In the pQCD based analysis at large  $x$ , the anti-parallel helicity distributions are suppressed relative to the parallel ones, thus SU(6) is broken to  $SU(3)^\uparrow \times SU(3)^\downarrow$ . Also the relativistic effect due to the Melosh-Wigner rotation causes a suppression in the helicity distributions observed in deep inelastic scattering

compared to the quark spin distributions in the quark model [17]. Nevertheless, our model still retains the ratio  $u^\uparrow/s^\uparrow = 1/2$  at large  $x$  [7]. Thus helicity retention plus broken SU(6) imply immediately that  $u(x)/s(x) \rightarrow 1/2$  and  $\Delta q(x)/q(x) \rightarrow 1$  (for  $q = u, d$ , and  $s$ ) for  $x \rightarrow 1$ , and therefore the flavor structure of the  $\Lambda$  near  $x = 1$  is a region in which accurate tests of the pQCD based approach can be made.

From the power-law behaviors of Eq. (5), we write down a simple model formula for the valence quark distributions,

$$q^\uparrow(x) \sim x^{-\alpha}(1-x)^3; \quad q^\downarrow(x) \sim x^{-\alpha}(1-x)^5, \quad (8)$$

where  $q^\uparrow(x)$  and  $q^\downarrow(x)$  are the parallel and anti-parallel quark helicity distributions and  $\alpha$  is controlled by Regge exchanges with  $\alpha \approx 1/2$  for nondiffractive valence quarks. This model is not meant to give a detailed description of the quark distributions but to outline its main features in the large  $x$  region. Combining Eq. (8) with Eq. (7), we get,

$$\begin{aligned} u^\uparrow(x) &= d^\uparrow(x) = \frac{35}{64}x^{-\frac{1}{2}}(1-x)^3; & u^\downarrow(x) &= d^\downarrow(x) = \frac{693}{1024}x^{-\frac{1}{2}}(1-x)^5; \\ s^\uparrow(x) &= \frac{35}{32}x^{-\frac{1}{2}}(1-x)^3; & s^\downarrow(x) &= 0, \end{aligned} \quad (9)$$

which obviously satisfies that  $u(x)/s(x) = 1/2$  and  $\Delta q(x)/q(x) = 1$  (for  $q = u, d$  and  $s$ ) as  $x \rightarrow 1$ .

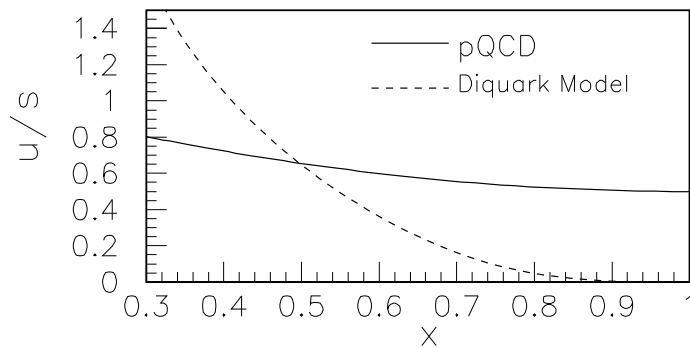


Figure 1: The ratio  $u(x)/s(x)$  of the  $\Lambda$  from the pQCD based approach (solid curve) and the SU(6) quark-diquark model (dashed curve).

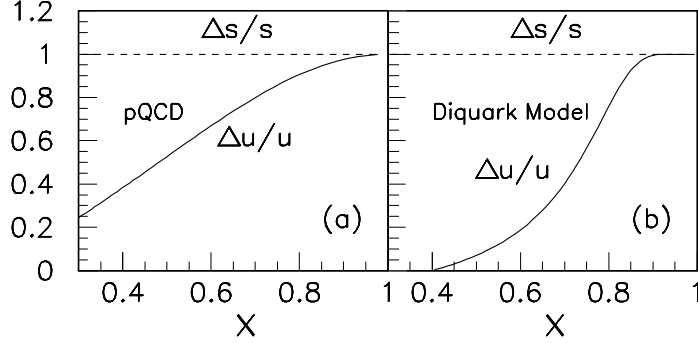


Figure 2: The ratios  $\Delta s(x)/s(x)$  for the valence strange quark (dashed curves) and  $\Delta u(x)/u(x)$  for the up and down valence quarks (solid curves) of the  $\Lambda$  from (a) the pQCD based approach and from (b) the SU(6) quark-diquark model.

In Fig. 1 we compare the  $x$ -dependence for the ratio  $u(x)/s(x)$  of the unpolarized quark distributions at large  $x$  in the two approaches and notice a significant difference between the predictions from the quark-diquark model and the pQCD motivated model. We also present in Fig. 2 the ratios  $\Delta s(x)/s(x)$  and  $\Delta u(x)/u(x)$ . We find that in both the quark-diquark model and the pQCD motivated model, the dominant valence  $s$  quark is totally positively polarized, and the non-dominant valence  $u$  and  $d$  quarks are also positively polarized at large  $x$ , though they have net zero contributions to the  $\Lambda$  spin. This supports the viewpoint [19] that one cannot neglect the contribution from the  $u$  and  $d$  quarks, in order to measure the strange quark polarization of a proton  $\Delta s(x)$  from the  $\Lambda$  polarization of unpolarized electron deep inelastic scattering (DIS) process on a polarized proton target [20]. Though the qualitative features are similar for the ratio  $\Delta u(x)/u(x)$  in the two approaches, the magnitude of  $\Delta u(x)$  in the quark-diquark model should be more suppressed than that from the pQCD based approach at large  $x$  due to the large suppression of  $u(x)$ . Therefore there is also difference in the spin structure for different flavor valence quarks of the  $\Lambda$  near  $x = 1$ .

We now discuss the processes that can serve to test the above predictions. Direct measurement of the quark distributions of the  $\Lambda$  is difficult, since the  $\Lambda$  is a charge-neutral particle which cannot be accelerated as incident beam and its short life time

makes it also difficult to be used as a target. Thus one may extend the analysis of this work to a charged hyperon, such as  $\Sigma^\pm$  or  $\Xi^-$ , which might be used as beam in Drell-Yan processes to test different predictions. However, we know that the quark distributions inside a hadron are related by crossing symmetry to the fragmentation functions of the same flavor quark to the same hadron, by a simple reciprocity relation [21]

$$q_h(x) \propto D_q^h(z), \quad (10)$$

where  $z = 2p \cdot q / Q^2$  is the momentum fraction of the produced hadron from the quark jet in the fragmentation process, and  $x = Q^2 / 2p \cdot q$  is the Bjorken scaling variable corresponding to the momentum fraction of the quark from the hadron in the DIS process. Although such an approximate relation may be only valid at a specific scale  $Q^2$  near  $x = 1$  and  $z = 1$ , it can provide a reasonable connection between different physical quantities and lead to different predictions about the fragmentations based on our understanding of the quark structure of a hadron [15, 22]. From another point of view, there are both experimental evidence and theoretical arguments to indicate the limitation of this relation for the physical application. Since our present knowledge on the fragmentation functions is still poor, we may consider our study as a phenomenological method to parameterize the quark to  $\Lambda$  fragmentation functions, and the validity and reasonableness of the method can be checked by comparison with the experimental data on various quark to  $\Lambda$  fragmentation functions. Thus we can use various  $\Lambda$  fragmentation processes to test different predictions.

In principle we can test the different predictions by a measurement of a complete set of quark to  $\Lambda$  fragmentation functions. One promising method to obtain a complete set of polarized fragmentation functions for different quark flavors is based on the measurement of the helicity asymmetry for semi-inclusive production of  $\Lambda$  hyperons in  $e^+e^-$  annihilation on the  $Z^0$  resonance [14]. There is also a recent suggestion [15] to measure a complete set of quark to  $\Lambda$  unpolarized and polarized fragmentation functions for different quark flavors by the systematic exploitation of unpolarized and polarized  $\Lambda$  and  $\bar{\Lambda}$  productions in neutrino, antineutrino and polarized electron DIS processes. However, in practice we do not need such systematic studies of quark to



$\Lambda$  fragmentations before we can test the different predictions.

Some physical quantities related to the  $\Lambda$  fragmentations in specific regions can provide direct test of different predictions. There have been suggestions that the ratio  $\Delta D_u^\Lambda(z)/D_u^\Lambda(z)$  can be measured from polarized electron DIS process [19] and neutrino DIS process in the region  $y \simeq 1$  [15, 23]. Although the net  $\Delta u$  might be zero or negative, and the magnitude also differs in different predictions, the results of the present work tell us that  $\Delta D_u^\Lambda(z)/D_u^\Lambda(z)$  is positive at large  $z$ , something unexpected from naive theoretical expectations. There have been also calculations [23, 24] of  $\Lambda$  production in several processes, based on simple ansatz such as  $\Delta D_q^\Lambda(z) = C_q(z)D_q^\Lambda(z)$  with constant coefficients  $C_q$ . From the present work we know that there are many unreasonable assumptions on the detailed  $z$ -dependence of the fragmentation in the previous calculations, therefore their conclusions [23, 24] lack predictive power and need to be re-checked with reasonable physical inputs for various fragmentation functions.

The results presented in this letter should be considered as only valid for the valence quarks, which are expected to play the dominant role in the regions of  $x \geq 0.4$  (or  $z \geq 0.4$ ), where we still need reliable data. In the small and medium  $x$  (or  $z$ ) regions, the sea of the  $\Lambda$  is expected to play an important role, and there are many details that have to be addressed in order to understand the physics in these regions. We also notice that the study of this work can be directly extended to other hadrons, such as  $\Sigma$ ,  $\Xi$ , or even to heavier flavor hadrons such as  $\Lambda_c$ , which may contribute as backgrounds to the  $\Lambda$  production or serve as new directions to test different physics concerning hadron structure. We do not expect to address all the vast issues in this brief letter, and more detailed analysis will be given elsewhere [25, 26].

We point out here that our prediction of positively polarized  $u$  and  $d$  quarks inside  $\Lambda$  at large  $x$  has been supported by the available data of  $\Lambda$ -polarization in  $e^+e^-$ -annihilation near the  $Z$ -pole [25] and also by the most recent HERMES experiment on longitudinal spin transfer to the  $\Lambda$  in deep elastic scattering of polarized positron on the nucleon target [27]. From the results given in Ref. [25], we found that the quark-diquark model gives a very good description of the available experimental data of the  $\Lambda$ -polarization in  $e^+e^-$ -annihilation near the  $Z$ -pole. The pQCD based analysis can

also describe the data well by taking into account the suppression due to the Melosh-Wigner rotation effect in the quark helicities compared to the naive SU(6) quark model spin distributions [17]. We also calculate and present here the longitudinal spin transfer to the  $\Lambda$  in deep elastic scattering of polarized lepton on the nucleon target defined by [19, 27]

$$D_{LL'}^\Lambda = \frac{\sum_q e_q^2 q_N(x) \Delta D_q^\Lambda(z)}{\sum_q e_q^2 q_N(x) D_q^\Lambda(z)}, \quad (11)$$

where  $e_q$  is the charge of the quark,  $q_N(x)$  is the quark distribution inside the nucleon, and  $D_q^\Lambda(z)$  and  $\Delta D_q^\Lambda(z)$  are the unpolarized and polarized quark to  $\Lambda$  fragmentation functions calculated by the relation (10). Our predictions are shown in Fig. 3, in comparison with the recent HERMES data [27]. We notice that the available HERMES data point is consistent with both the quark-diquark model and the pQCD based predictions within the present err-bar, and this seems to support the positive  $u$  and  $d$  polarizations at large  $x$  inside the  $\Lambda$  predicted in our work. Unfortunately, it is still not possible to make a clear distinction between the two different predictions of the flavor and spin structure of the  $\Lambda$  by the available data with the present statistical precision, and also in each model there is still some freedom to adjust the parameters for a better fit of the detailed features [25]. It is also necessary to point out that the available HERMES data should not be considered as in contradiction with the prediction of negative polarizations of  $u$  and  $d$  quarks inside the  $\Lambda$  [14], since the positive polarizations of  $u$  and  $d$  at large  $x$  do not rule out the net negative  $u$  and  $d$  polarizations inside the  $\Lambda$  integrated over whole  $x = 0 \rightarrow 1$ .

In summary, we studied the flavor and spin structure of the  $\Lambda$  at large  $x$  and found it is a region that can provide clean tests of different predictions. We also found that the up and down quarks should be positively polarized at large  $x$ , even though their net spin contributions to the  $\Lambda$  might be zero or negative. This prediction has been supported by the available data of  $\Lambda$ -polarization in  $Z$  decays and also by the most recent HERMES result of spin transfer to the  $\Lambda$  in deep elastic scattering of polarized lepton on the nucleon target. Thus  $\Lambda$  Physics is a frontier with rich physics content that deserves attention both theoretically and experimentally.

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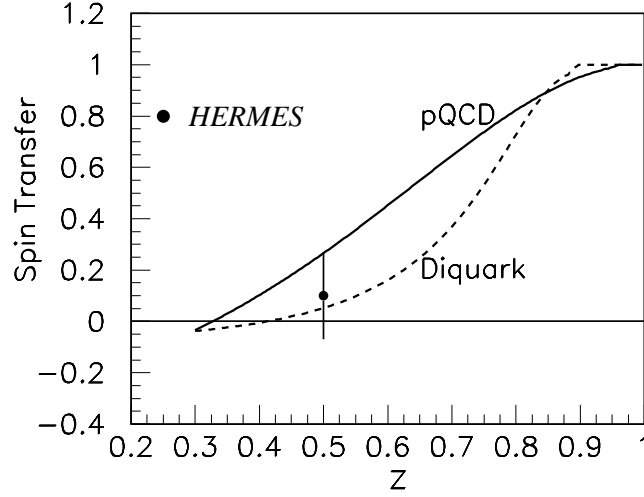


Figure 3: The predictions of the longitudinal spin transfer to the  $\Lambda$  in deep inelastic scattering of polarized lepton on the nucleon target from the simple pQCD based approach (solid curve) and the SU(6) quark-diquark model (dashed curve). The data point is the most recent result by the HERMES collaboration [27].

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## References

- [1] For reviews, see, e.g., H.-Y. Cheng, Int. J. Mod. Phys. **A 11** (1996) 5109;  
G.P. Ramsey, Prog. Part. Nucl. Phys. **39** (1997) 599.  
For a recent discussion, see, B.-Q. Ma, I. Schmidt, and J. Soffer, Phys. Lett. **B 441** (1998) 461.
- [2] S.J. Brodsky, J. Ellis, and M. Karliner, Phys. Lett. **B 206** (1988) 309;  
J. Ellis and M. Karliner, Phys. Lett. **B 213** (1988) 73; **B 341** (1995) 397.
- [3] See, e.g., S.J. Brodsky and B.-Q. Ma, Phys. Lett. **B 381** (1996) 317, and references therein.
- [4] For a recent review, see, e.g., S. Kumano, Phys. Rep. **303** (1998) 183.
- [5] B.-Q. Ma, Phys. Lett. **B 274** (1992) 111;  
C. Boros, J.T. Londergan, and A.W. Thomas, Phys. Rev. Lett. **81** (1998) 4075.
- [6] G.R. Farrar and D.R. Jackson, Phys. Rev. Lett. **35** (1975) 1416.
- [7] S.J. Brodsky, M. Burkardt, and I. Schmidt, Nucl. Phys. **B 441** (1995) 197.
- [8] R. Carlitz, Phys. Lett. **B 58** (1975) 345; J. Kaur, Nucl. Phys. **B 128** (1977) 219;  
A. Schäfer, Phys. Lett. **B 208** (1988) 175.
- [9] B.-Q. Ma, Phys. Lett. **B 375** (1996) 320.
- [10] W. Melnitchouk and A.W. Thomas, Phys. Lett. **B 377** (1996) 11.
- [11] U.K. Yang and A. Bodek, Phys. Rev. Lett. **82** (1999) 2467.
- [12] M. Boglione and E. Leader, preprint VUTH-99-24 (1999). e-Print Archive: hep-ph/9911207
- [13] SM Collab., B. Adeva *et al.*, Phys. Lett. **B 369** (1996) 93; **B 420** (1998) 180.
- [14] M. Burkardt and R.L. Jaffe, Phys. Rev. Lett. **70** (1993) 2537.

- [15] B.-Q. Ma and J. Soffer, Phys. Rev. Lett. **82** (1999) 2250.
- [16] S. J. Brodsky, T. Huang, and G. P. Lepage, in *Particles and Fields-2*, Proceedings of the Banff Summer Institute, Banff, Alberta, 1981, edited by A. Z. Capri and A. N. Kamal (Plenum, New York, 1983), p. 143.
- [17] B.-Q. Ma, J. Phys. **G 17** (1991) L53;  
B.-Q. Ma and Q.-R. Zhang, Z. Phys. **C 58** (1993) 479.
- [18] R. Blankenbecler and S.J. Brodsky, Phys. Rev. **D 10** (1974) 2973;  
J.F. Gunion, Phys. Rev. **D 10** (1974) 242;  
S.J. Brodsky and G.P. Lepage, in Proc. 1979 Summer Inst. on Particle Physics, SLAC (1979).
- [19] R.L. Jaffe, Phys. Rev. **D 54** (1996) R6581.
- [20] W. Lu and B.-Q. Ma, Phys. Lett. **B 357** (1995) 419.
- [21] V.N. Gribov and L.N. Lipatov, Phys. Lett. **B 37** (1971) 78; Sov. J. Nucl. Phys. **15** (1972) 675.
- [22] S.J. Brodsky and B.-Q. Ma, Phys. Lett. **B 392** (1997) 452.
- [23] A. Kotzinian, A. Bravar, and D.von Harrach, Eur. Phys. J. **C 2** (1998) 329.
- [24] C. Boros and Z. Liang, Phys. Rev. **D 57** (1998) 4491.
- [25] B.-Q. Ma, I. Schmidt, and J.-J. Yang, Phys. Rev. **D 61** (2000) 034017.
- [26] B.-Q. Ma, I. Schmidt, and J.-J. Yang, Preprint USM-TH-81, hep-ph/9907556, Nucl. Phys. **B** (2000) to be published.
- [27] The HERMES Collab., A. Airapetian *et al.*, hep-ex/9911017.